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Optimisation of Weld Seam Configurations Using a Genetic Algorithm

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Abstract

The main task of high performance electrical contacts is the transmission of electrical power with low power dissipation. The decisive value to calculate the electrical losses of a contact is the resistance of the contact configuration. The electrical resistance can be decreased applying laser welded connections. This promising joining technology offers the opportunity to vary the contact area as well as its position in the joining zone. Especially the geometrical shape of the contact area enables a high potential to reduce the contact resistance. This work presents a method to optimise the geometrical shape of the weld seam in order to minimise the resistance of the electrical contact. A solution is proposed to calculate the optimum weld seam shape by the use of a genetic algorithm (GA) linked with an electro-thermal FEM simulation. The genetic algorithm compiles alternative weld seam shapes while the FEM simulation determines their electro-thermal properties. The optimised result is further verified within an experimental study. The proposed method is applied to design the electrical contacts between battery cells of a high voltage automotive battery system for electric and hybrid electric cars.

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Keywords: electrical contacts; laser beam welding; genetic algorithm; electro-thermal FEM

1. Introduction

Joining technologies to create the electrical contacts of high performance devices is still an important topic. These technologies do not only need to meet production related requirements such as a short cycle time and a high degree of automation, but also have to fulfil the task to transmit electrical power with low power dissipation. Consequently a long-term stable joint with a high conductivity of the connectors is required. The decisive value to calculate the electrical losses of a contact is the resistance of the contact configuration.

To reduce the electrical losses of the contact, laser beam welding can be applied. Thus, on the one side a material locking connection with low contact resistances can be generated, on the other side the production related demands are met [1-4]. The remote laser beam welding process offers the opportunity to vary the contact area as well as its position in the joining zone. Further studies [5, 6] showed a significant dependence of the geometrical shape of the contact area and the contact resistance. The prediction of the optimised shape of the contact area is very complex regarding three-dimensional contact configurations. Due to that empirical approaches are not suitable to determine the optimum. This work presents a method to optimise the geometrical shape of the weld seam in order to minimise the resistance of the electrical contact under consideration of the given boundary conditions.

The introduced optimisation method is applicable for any electrical connection in lap joint configuration. One application for such joints is the electrical contact between Li-ion batteries in a traction battery for electric or hybrid-electric cars. The optimised weld seam configuration is calculated and applied to a battery pack.

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2. Fundamentals

2.1. Electrical Contact Losses

An electrical contact resistance determines the electrical loss in a current-carrying component, which dissipates in the form of thermal energy. In high performance devices e.g. battery systems of electric vehicles (EVs) the electrical losses caused by the contacts can amount to significantly high amounts [6, 7]. They add up over several hundred contacts in a traction battery at currents of up to 300 A. Hence, these losses are directly connected to a reduction of the EV range [7].

For laser welded joints the electrical contact resistance and the contact area of two surfaces correlate inverse proportional; however, a large contact area results in a major heat input on the battery cell during the welding process. Temperatures of the battery cell of over 100°C cause severe damages [9, 10]. In addition the process time increases with larger contact areas as well. Consequently the contact area is defined under the following restrictions:

- maximum temperature of the battery cell terminal of 100°C
- ampacity of 45 – 240 A, dependent on the Li-ion cell [11]
- process time < 2 s per contact
- sufficient mechanical strength of the battery contact

Nomenclature

A	cross-section area of the conductor
c_p	heat capacity
E	electric field
I	electric current
I_C	applied electric current
I_n	individual
J	current density
K	heat conductivity
n_P	population size
$P_{Ell.}$	elitism operator
$P_{Mut.}$	mtation operator
$P_{Rec.}$	recombination operator
T_0	reference temperature
V	electric potential
Z	objective value
α_T	temperature coefficient
ΔV_i	potential difference of the ideal contact area
ΔV_m	potential difference of the individual (V_1-V_2)
P	density
ρ_0	specific electrical resistance
o	electric conductivity

2.2. Electro-thermal FEM Simulation

The electro-thermal FEM simulation allows a calculation of the electrical potential of complex contact geometries loaded with a certain current. With the potential difference between two points and a given electric current the resistance for the contact geometry can be determined [12]. The following basic equations (1-5) are implemented in the thermo-electric FEM simulation. The thermal heating is described by a temperature-dependent electric conductivity (5) and the well known Joule effect.

Electric current:

$$I = \int_A J\,dA = \sigma \int_A E\,dA \qquad (1)$$

Electric field:

$$E = \frac{J}{\sigma} \qquad (2)$$

$$E = -\nabla V \qquad (3)$$

Electric potential:

$$V = \int_s E\,ds \qquad (4)$$

Temperature-dependent electric conductivity:

$$\sigma = \frac{1}{\rho_0 \cdot (1+\alpha_T \cdot (T-T_0))} \qquad (5)$$

The implementation in the FEM solver is derived using the law of conservation of charge and is summarised by equation (6).

Conservation of Charge:

$$\nabla \cdot (-\sigma \cdot \nabla V) = 0 \qquad (6)$$

2.3. Genetic Algorithm

A genetic algorithm (GA) belongs to the evolutionary algorithms and is based on a stochastic search technique. The GA depends on the natural biological principle of evolution. This optimisation method evaluates single solutions (individuals) within a solution set (population). The design attributes of the individuals are coded analogue to a chromosome. Using a target function (fitness function) the best individuals survive in order to find a good or the best solution. Accordingly the methods of natural selection (genetic operators), selection, elitism, reproduction, recombination and mutation are implemented in the iterative solving process. [14, 15]

In the first step the initial population is created and the fitness value for each individual is determined. The fitness value is assigned based on the rank of the individual within the population. This assignment guarantees a constant selection pressure, independent of the quality of the individual. The selection pressure affects the speed of convergence as well as the ability of a premature convergence [16].

As long as the stop criterion is not fulfilled, a new generation will be established. Therefore the fitness value is assigned to each individual and is matched to the values of all individuals. Based on the fitness values, the individuals (parents) are selected for the production of new individuals (children). This step is summarised in the selection and reproduction of individuals. [14]

3. Optimisation Method

3.1. Optimisation Problem

A solution is proposed to calculate the optimum weld seam shape by the use of a genetic algorithm (GA) linked with an electro-thermal FEM simulation. Within the FEM simulation the electrical resistance for one specific shape of the contact area is calculated. The shape of the contact area is assembled by single quadrates (pixels) with an area of 1 mm². The position of these elements in the overlap area is varied until a minimum of the electrical resistance of the joint is found.

The optimisation model evaluates the electro-thermal properties and compiles, based on a genetic algorithm, alternative weld seam shapes. The principal arrangement of a contact area for an electric contact is displayed in Figure 1. The domain of definition is the geometrical frame for the contact area. A constant number of quadrates serves as the given contact area produced by the welding process. The electricity is transmitted only by these elements; the other area of the domain of definition is electrically insulated. The electrical resistance can be calculated by the potential difference between the positions V_1 and V_2 and the supplied current I_c.

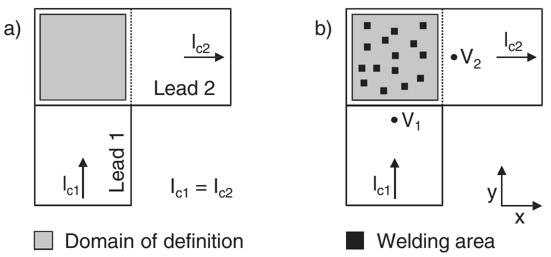

Figure 1: a) Domain of definition for a lap joint configuration of two leads; b) random arrangement of a predefined contact area with 15 electrically conductive elements (welding area) and the positioning of the potentials V_1 and V_2 at a given current I_c

3.2. Setting of the Optimisation Model

The initial population is generated by a random set of coordinates of the corresponding pixels. The fitness value of each individual is calculated from the results of the electro-thermal simulation. For every set of coordinates the geometry is built, the boundary conditions and the material model are set. Furthermore, the mesh is individually generated. After solving the FEM model, the potential difference is transferred back to the optimiser in order to calculate the fitness value. If the stop criterion is not fulfilled, a new population is built using the genetic operators. The sequence of the optimisation method is shown in Figure 2.

3.3. Characteristic of the Genetic Algorithm

The GA process utilizes a random initial population with a standard population size of 20 individuals according to the suggestions of Grefenstette [15] and Jakiela [17]. This number of individuals turned out to be a good compromise for an efficient convergence of the algorithm. The design attributes of an individual, the geometrical set of n welded pixels respectively, is coded in a vector with n X- and n Y-coordinates, see Figure 3. The vector of the individuals is checked by an additional function. This function analyses the position of the elements under the following boundary conditions:

- pixels are in the domain of definition (cp. Figure 1)
- no overlapping of two pixels

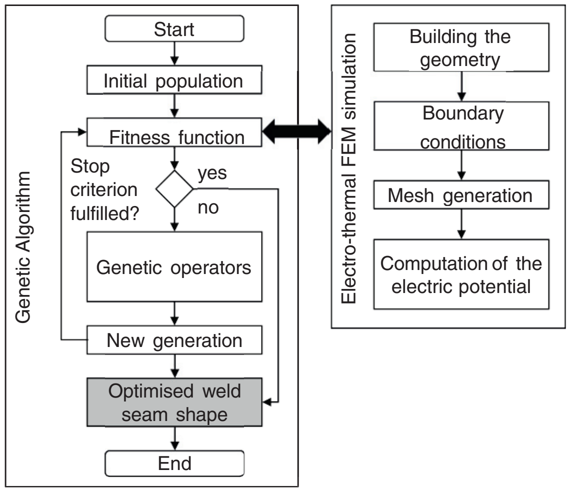

Figure 2: Sequence of the optimisation method

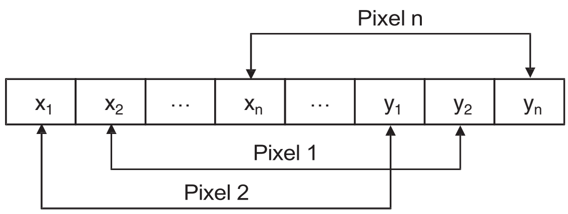

Figure 3: Coding of the design attributes of an individual with n pixels

If one of the boundary conditions is not fulfilled, a new vector is generated. The valid vector is then transferred to the FEM model, the mesh and boundary conditions are generated and the electric properties are calculated.

The objective value Z is calculated by the ratio of the potential difference between the ideal connection of the two leads with a maximum contact area ΔV_i and the potential difference of an individual ΔV_m at predefined positions in the FEM model (according to Eq. 7). The maximum contact area is equal to the domain of definition (cp. Figure 1).

Objective value Z:

$$Z = \frac{\Delta V_m}{\Delta V_i} \tag{7}$$

A non-linear rank-based fitness assignment is used to determine the fitness values of the individuals. The rank-based fitness assignment sorts the populations according to their objective values. That means, that the fitness value assigned to each individual depends only on its position within the population. Thus a premature convergence can be prevented in this case (cp. Section 2.3).

After the fitness value assignment the steps selection, recombination and mutation follow. For the selection strategy the stochastic universal sampling and elitism based on [14] are chosen. The elitism operator selects the two best individuals ($P_{Eli.} = 0,1$). For the recombination 28 parents are chosen ($P_{Rec.} = 0,7$), the rest of the selected parents mutate ($P_{Mut.} = 0,2$) with a mutation rate of 0,01. Figure 4 illustrated the process of selection and reproduction. This GA routine will run until the stop criterion of a maximum number of 80 generations is reached. Within 80 generations a proper solution can be found within a justifiable calculation time. The process of selection and reproduction for a population size $n_P = 20$ is illustrated in Figure 4.

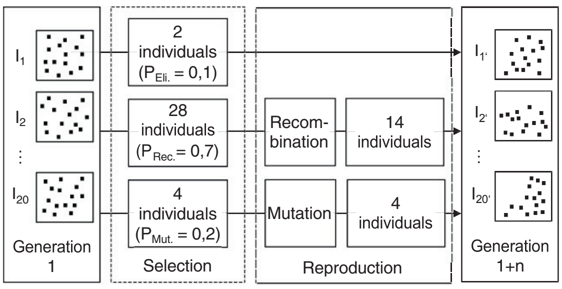

Figure 4: Process of selection and reproduction for a population size $n_P = 20$; the population consists of the individuals I_1 to I_{20}

3.4. Definition of the Electro-thermal FEM Model

The potential field is calculated using the FEM software Comsol Multiphysics with the Conductive Media DC module. The Ohmic heating was simulated with the Heat Transfer by Conduction module. The geometry and boundary settings of the inward current I_c and the ground is displayed in Figure 5. A free tetrahedral mesh in the area I and III was generated with a minimal element size of 0,8 mm. In area II a free triangular mesh is used to build the insulating section between the two leads. The minimal element size in this area is 0,2 mm. To carry the current between both leads the square pixels are not insulted. All analysis were done for aluminum Al 99,5. The necessary data for the material model is shown in Table 1.

3.5. Verification of the Optimisation Method

For the verification of the optimisation method the optimal weld seam shape of a tensile shear test specimen was calculated. In this case the optimal weld seam shape is already known [6]. The geometrical set of the model is axially symmetric to reduce the calculation time. The calculated seam shapes for 20, 40 and 80 generations and a given contact area of 24 mm² (sheet thickness of 1 mm) are displayed in Figure 6. The optimisation was stopped after 80 generations.

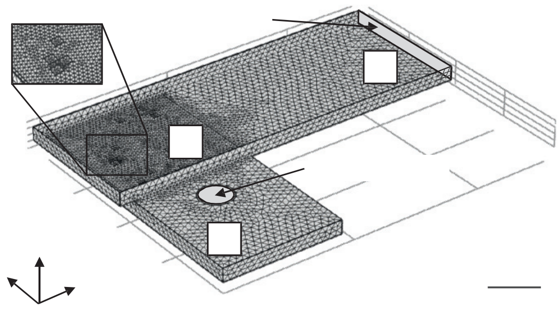

Figure 5: Mesh and boundary settings of the FEM model; free tetrahedral mesh in area I and III, free triangular mesh in area II

Table 1: Data of the considered material aluminum Al 99,5 [18]; the specific electrical resistance ρ_0 was determined by experiment

Parameter	Al 99,5	Unit
Heat conductivity k	215	W/(m·k)
Density ρ	2700	Kg/m³
Heat capacity c_p	900	J/(kg·K)
Temperature coefficient α_T	0,0039	1/K
Initial temperature T_0	295	K
Specific electrical resistance ρ_0	$1,69\cdot10^{-8}$	Ω·m

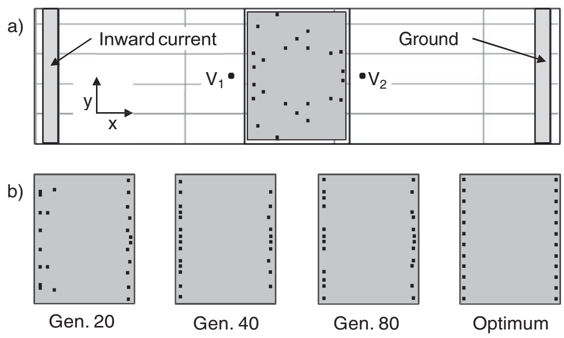

Figure 6: a) Tensile shear test geometry with the positions of the potentials V_1 and V_2 and a pixel configuration from the initial population; b) calculated seam shape configurations of the best individuals of generation 20 to 80

The final step is a uniform positioning of the pixels by the user in order to save additional calculation time. The contact resistance of the welded optimised seam shape was measured with the four probe measurement technique (published in [5, 7, 19]). With the simulation model a resistance of 15,53 μΩ was calculated; the experiment showed a contact resistance of 16,09 μΩ. The deviation between experiment and simulation is 0,56 μΩ (3,5 % according to the experimental data). With this verification the optimisation method can be applied to any contact configurations with a lap joint configuration.

The characteristic of the objective values versus the number of calculated generations for the shear tensile test geometry is illustrated in Figure 7. The objective value of Z_{i_80} = 1,09 was calculated for the best individual of generation 80. The optimum reveals an objective value of Z_{i_opt} = 1,08.

4. Results

4.1. Geometrical Setup and Boundary Conditions of a Battery Pack

One application of the optimisation method is the cell contacting of a battery pack that consists of several Li-ion batteries. The electrical connection is created by a cell connector. This cell connector is made out of aluminum. The cell terminals are made out of copper (anode) and aluminum (cathode). The copper terminal is designed using a copper-aluminum hybrid part to guarantee a joint between cell connector and cell terminal with similar materials.

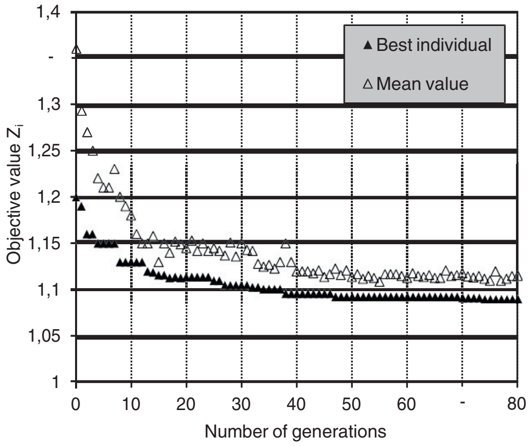

Figure 7: Objective values Z_i of the best individuals and the mean values of the populations versus the number of calculated generations

For this application a contact area of 15 mm² was specified in order to fulfill the requirements of the welding time (< 2 sec. per contact) and the maximum terminal temperature (< 100 °C), cp. Section 2.1. The cell connector enables a series circuit of two separate cells, connected in parallel, see Figure 8.

Two contact conditions have to be considered to determine the optimised weld seam shape of the battery pack with the introduced electrical circuit. The first contact condition (I) consists of one terminal and the cell connector. The second condition (II) includes the current flow of the first and second terminal. The two contact conditions are illustrated in Figure 9.

4.2. Optimised Weld Seam Shape of a Battery Pack

The weld seam configurations for contact conditions I and II were determined by the discussed optimisation method. The results of contact condition I are illustrated in Figure 10. The objective value Z_I was calculated by equation (8). The ideal contact condition (Z_{I_i} = 1) exhibits a contact area of 288 mm².

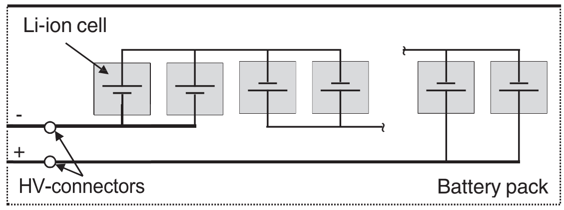

Figure 8: Series circuit of two separate cells connected in parallel within a battery pack and high voltage (HV)-connectors

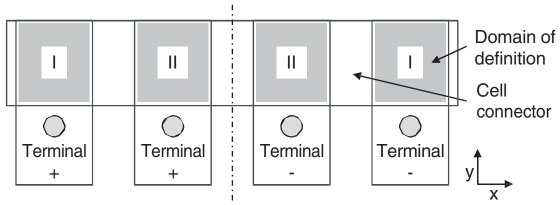

Figure 9: Series circuit of two separate cells connected in parallel within a battery pack and the contact conditions I and II

The initial population reveals a value of Z_{I_0} = 1,32. After the optimisation an objective value of Z_{I_opt} = 1,13 could be reached. That means that the electrical resistance of the presented weld seam configuration of contact condition I exceeds the ideal value by only 13 %, although the contact area is significantly smaller. This weld seam shape allows a short current flow by the use of the maximum lead cross section at the same time. The welded area enables a parallel circuit of the two leads which results in the reduction of the contact resistance.

The optimised result of contact condition II is shown in Figure 11. The objective value Z_{II} consists of the mean value of the potential differences $\Delta V_1 = V_1 - V_3$ and $\Delta V_2 = V_2 - V_3$. The potential difference ΔV_1 takes the current flow of contact condition I into account. Potential difference ΔV_2 is equal to the potential difference of contact condition I. For the fitness evaluation both values had to be considered, cp. Equation 9. The initial population reveals an objective value of Z_{II_0} = 1,29. After the optimisation an objective value of Z_{II_opt} = 1,11 was reached. In this case the weld seam configuration of contact condition II exceeds the ideal value by 11 %.

The optimised weld seam shape exhibits an area at the bottom side of the domain of definition where no electrical contact is necessary. The reason for this is the inward current flow of the second cell terminal. The current flows of the cell connector and the terminal result in a balanced electric field in this area. Consequently the four pixels in the upper area of the domain of definition are more beneficial, because they yield a parallel circuit of cell connector and cell terminal. The pixels on the right and lower side of the domain of definition offer a short current flow between the ground and the second terminal.

The developed weld seam shapes were applied to a battery pack with eight Li-Ion cells and an electric circuit according to Figure 8. The cell connectors were welded using an

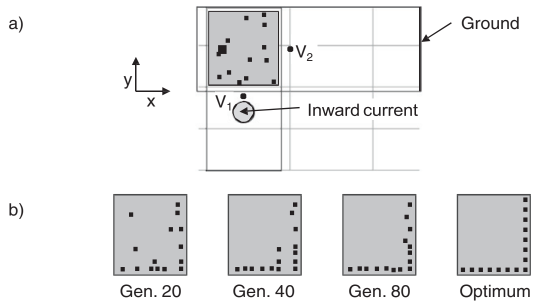

Figure 10: a) Contact condition I with the positions of the potentials V_1 and V_2 and a pixel configuration from the initial population; b) calculated seam shape configurations of the best individuals of generation 20 to 80

Objective value Z_I:

$$Z_I = \frac{\Delta V_m}{\Delta V_i} \tag{8}$$

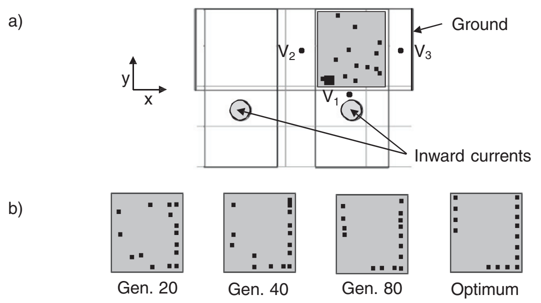

Figure 11: Contact condition II with the positions of the potentials V_1, V_2 and V_3 and a pixel configuration from the initial population; b) calculated seam shape configurations of the best individuals of generation 20 to 80

Objective value Z_{II}:

$$Z_{II} = \frac{\frac{\Delta V_{m1}}{\Delta V_{i1}} + \frac{\Delta V_{m2}}{\Delta V_{i2}}}{2} \tag{9}$$

yitterbium-doped YAG single mode (SM) fiber laser by IPG Photonics. This laser beam source emits continuous wave (cw) laser radiation with a wavelength of $\lambda = 1070$ nm. To achieve a weld seam width of 1 mm, beam oscillation with an oscillation amplitude of A_{osc} = 0,25 and an oscillation frequency of f = 200 Hz was applied. The welding process was performed with a laser power of P_L = 2700 W and a welding velocity of v_w = 33,3 mm/s. The cell connectors were clamped by insulated elements with a shielding gas supply for every terminal. The welding time was 15 s for the whole battery pack. The successfully welded battery pack with clamping elements and shielding gas supply is shown in Figure 12.

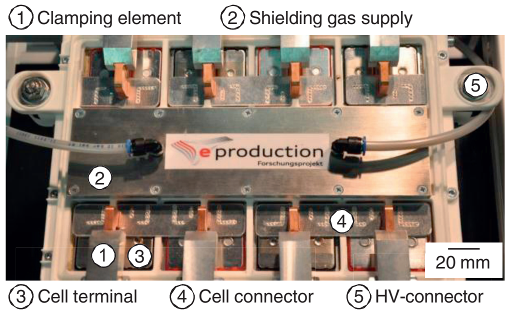

Figure 12: Welded battery pack with eight Li-Ion-cells; welding parameters: laser power P_L = 2700 W, welding velocity v_w = 33,3 mm/s, beam oscillation amplitude A_{osc} = 0,25 and beam oscillation frequency f = 200 Hz

5. Summary

For high performance devices electrical connections with low electrical losses are required. In this paper a method is presented to optimise the electrical resistance of lap joint configurations applying remote laser beam welding. The optimisation method consists of an electro-thermal FEM simulation of the joint geometry to determine the potential difference of the welded area. A linked optimiser employs a genetic algorithm to create and evaluate single weld seam shapes. The optimisation process was verified by a standard testing specimen, for which the optimal weld seam configuration is already known. The approved optimisation was used to determine the weld seam shapes of a battery pack with eight Li-ion cells. The optima were found for the two contact conditions, which occur at the given electric circuit of the battery cells. The calculated weld seam shapes were successfully tested.

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References

[1] Bayer E. Laser Applications for "Green-Cars". In: Proceedings of European Automotive Laser Applications (EALA) - 13th, Bad Nauheim, Germany. Vincentz Network 2013.
[2] Weigl M, Grimm A, Frick T, Schmidt M. Laser Welding of Dissimilar Copper-Aluminum Connections by Means of Roll-Cladded Inserts. In: Proceedings of the 29th International Congress on Applications of Lasers & Electro-Optics (ICALEO), Anaheim CA, USA. Laser Institute of America 2010; p. 554-561.
[3] Plapper P, Solchenbach T, Cai W. Laser Beam Joining of Li-Ion Battery Module Assembly. In: Proceedings of European Automotive Laser Applications (EALA) - 14th, Bad Nauheim, Germany. Vincentz Network 2013.
[4] Lee S, Kim T, Hu S. Joining Technologies for Automotive Lithium-Ion Battery Manufacturing. ASME 2010 International Manufacturing Science 2010; p. 1-9.
[5] Schmidt P A, Schweier M, Zaeh M F. Joining of Lithium-Ion Batteries Using Laser Beam Welding: Electrical Losses of Welded Aluminum and Copper Joints. In: Proceedings of the 31th International Congress on

Applications of Lasers & Electro-Optics (ICALEO), Anaheim CA, USA. Laser Institute of America 2012; p. 915-923.

[6] Schmidt P A, Pauleser T, Zaeh M F. eProduction of automotive battery systems at AUDI AG. Smart EV and HEV Battery Production, Darmstadt. International Quality & Production Center (IQPC) 2013.

[7] Taheri P, Hsieh S, Bahrami M. Investigating electrical contact resistance losses in lithium-ion battery assemblies for hybrid and electric vehicles. Journal of Power Sources 196 2012; p. 6525–6533.

[8] Sievers M, Sievers U, Mao S. Thermal modelling of new Li-ion cell design modifications. Forschung im Ingenieurwesen 74 2010; p. 215-231.

[9] Araki K, Sato N. Chemical transformation of the electrode surface of lithium-ion battery after storing at high temperature. Journal of Power Sources 124 2003; p. 124-132.

[10] Vetter J, Novák P, Wagner M, Veit C, Möller K, Besenhard J, Winter M, Wohlfahrt-Mehrens M, Vogler C, Hammouche A. Ageing mechanisms in lithium-ion batteries. Journal of Power Sources 147 2005; p. 269-281.

[11] Pompetzki M. Challenges in Design and Manufacturing of Lithium-Ion Battery Cells for Battery Electrical Vehicles. In: Proceedings of 5th Battery Conference, Aachen, Germany. Haus der Technik 2013.

[12] Holland J. Adaptation in natural and artificial systems. Cambridge. MIT Press 1975.

[13] Böhme H. Mittelspannungstechnik. Berlin. Huss-Medien 2005. [14] Pohlheim H. Evolutionäre Algorithmen: Verfahren, Operatoren und Hinweise für die Praxis. Berlin. Springer-Verlag 1999.

[15] Grefenstette J. Optimization of Control Parameters for Genetic Algorithms. IEEE Trans. Syst., Man, Cybern. (IEEE Transactions on Systems, Man, and Cybernetics) SMC 16 1986; p. 122-128.

[16] Sivanandam S N, Deepa S N. Introduction to genetic algorithms. Berlin. Springer 2009.

[17] Jakiela M, Chapman C, Duda J, Adewuya A, Saitou K. Continuum structural topology design with genetic algorithms. Computer Methods in Applied Mechanics 186 200; p. 339-356.

[18] Gesellschaft für Verfahrenstechnik und Chemieingenieur-wesen, VDI-Wärmeatlas. Berlin. Springer 2002.

[19] Schürfer E. Elektrische Messtechnik: Messung elektrischer und nicht elektrischer Grössen. München. Hanser-Verlag 1990.